Mon. Not. R. Astron. Soc. **000**, 000–000 (0000) Printed 2 May 2008 (MN LaTeX style file v2.2)

In situ formation of the massive stars around SgrA*

M. Mapelli[1], T. Hayfield[1,2], L. Mayer[1,2], J. Wadsley[3]
[1] *Institute for Theoretical Physics, University of Zürich, Winterthurerstrasse 190, CH-8057, Zürich, Switzerland;* mapelli@physik.unizh.ch
[2] *Institute of Astronomy, ETH Zürich, ETH Honggerberg HPF D6, CH-8093, Zürich, Switzerland*
[3] *Department of Physics and Astronomy, McMaster University, Hamilton, ON L8S 4M1, Canada*

2 May 2008

ABSTRACT
The formation of the massive young stars surrounding SgrA* is still an open question. In this paper, we simulate the infall of an isothermal, turbulent molecular cloud towards the Galactic Centre (GC). As it spirals towards the GC, the molecular cloud forms a small and dense disc around SgrA*. Efficient star formation (SF) is expected to take place in such a dense disc. We model SF by means of sink particles. At $\sim 6\times10^5$ yr, $\sim 6000\,M_\odot$ of stars have formed, and are confined within a thin disc with inner and outer radius of 0.06 and 0.5 pc, respectively. Thus, this preliminary study shows that the infall of a molecular cloud is a viable scenario for the formation of massive stars around SgrA*. Further studies with more realistic radiation physics and SF will be required to better constrain this intriguing scenario.

Key words: methods: N-body simulations - Galaxy : centre - stars: formation - ISM: clouds

1 INTRODUCTION

The origin of young massive stars which crowd the Galactic Centre (GC) has been a puzzle for a long time. Most of the massive stars observed in the central parsec reside in one or perhaps two rotating discs (Genzel et al. 2003, hereafter G03; Paumard et al. 2006, hereafter P06). These discs have well-defined inner ($r_{in}\sim 0.04$) and outer radii ($r_{out}\sim 0.5$ pc). In fact, no OB stars have been found at a distance larger than ~ 0.5 pc (P06) from SgrA*, the source identified with the super massive black hole (SMBH). Similarly, the S stars observed at distances $\lesssim 0.02$ pc have randomly oriented motions and do not belong to the discs (G03; Ghez et al. 2005; Eisenhauer et al. 2005). The massive stars inside the discs are young (6 ± 2 Myr, P06) and must have formed over a short period (<2 Myr, P06). Their estimated initial mass function (IMF) is heavier than Salpeter's one (P06). The total mass in the discs cannot exceed $1.5\times10^4\,M_\odot$, but is more likely of the order of $5\times10^3\,M_\odot$ (P06).

Such stars cannot have formed *in situ* in 'normal' conditions, as the tidal forces exerted from the SMBH would have disrupted the parent molecular cloud (Levin & Beloborodov 2003; G03). Thus, an alternative scenario has been proposed, according to which a young cluster spiraled towards the GC and deposited its stars around SgrA* (Gerhard 2001; McMillan & Portegies Zwart 2003; Kim & Morris 2003; Gürkan & Rasio 2005; Fujii et al. 2008). However, even the latter scenario suffers from various shortcomings, such as the premature disruption of the cluster and the excessively long dynamical friction time. These problems have only been partially solved by assuming that the original clusters host intermediate-mass black holes (Portegies Zwart et al. 2006), or by using new computational schemes (Fujii et al. 2008). On the other hand, the problem of tidal forces exerted by the SMBH can be overcome if, at some point in the past, a dense gaseous disc existed around SgrA*. Such a disc could have formed due to the infall and tidal disruption of a molecular cloud. If the density in the disc was high enough, it might have become unstable to fragmentation and formed stars (Levin & Beloborodov 2003; G03; Goodman 2003; Milosavljevic & Loeb 2004; Nayakshin & Cuadra 2005; Alexander et al. 2008; Collin & Zahn 2008). The absence of massive stars at distances >0.5 pc from SgrA* supports this idea of *in situ* formation (Nayakshin & Sunyaev 2005; P06). This scenario is also favoured by the existence of two giant molecular clouds within ~ 20 pc from the dynamical centre of our Galaxy (Solomon et al. 1972). One of these two clouds (named M$-0.13-0.08$) is also highly elongated toward SgrA* and has a 'finger-like' extension pointing in the direction of the circumnuclear disc (Okumura et al. 1991; Ho et al. 1991; Novak et al. 2000, and references therein). Nayakshin, Cuadra & Springel (2007, hereafter NCS07) simulated star formation (SF) in a gaseous disc around SgrA*, and found encouraging results for this scenario. However, NCS07 assume that the gaseous disc was already in place when it started forming stars, and do not consider the process which lead to the formation of the disc itself. In this paper, we simulate the infall of a molecular cloud toward SgrA* and we study the formation of a dense gaseous disc

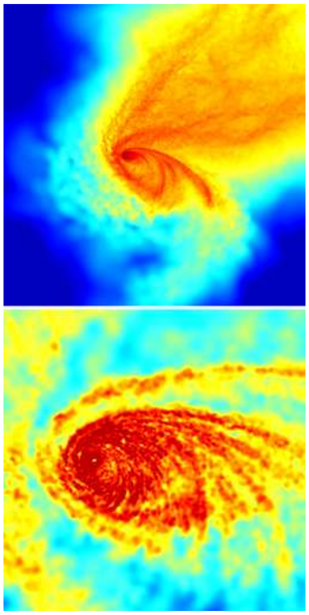

Figure 1. Upper panel: density map of gas, projected along the $x-$axis at $t = 3.3 \times 10^5$ yr. The frame measures 20 pc per edge and the centre is at 2 pc from the SMBH. The density goes from 2.23×10^{-2} (blue) to $4.45 \times 10^3\, M_\odot$ pc^{-2} (red) in logarithmic scale. Lower panel: zoom of the upper panel. The frame measures 1.5 pc per edge and the centre is at 0.3 pc from the SMBH. The density goes from 7.05×10^1 to $5.60 \times 10^3\, M_\odot$ pc^{-2} in logarithmic scale.

around the SMBH. We use a simple phenomenological recipe to simulate the SF process in the disc. Our results indicate that the infall of a molecular cloud is a viable scenario for the formation of massive stars around SgrA*.

2 MODELS AND SIMULATIONS

We ran N-body/Smoothed Particle Hydrodynamics (SPH) simulations of a molecular cloud evolving in a potential dominated by the SMBH. The SMBH is represented by a sink particle, with initial mass $M_{\rm BH} = 3.5 \times 10^6\, M_\odot$ (Ghez et al. 2003), sink radius $r_{acc} = 5 \times 10^{-3}$ pc and softening radius $\epsilon = 1 \times 10^{-3}$ pc. We also add a rigid potential, according to a density distribution $\rho(r) = \rho_0\, (r/c)^{-\alpha}$, where $\rho_0 = 1.2 \times 10^6\, M_\odot$ pc^{-3}, $c = 0.39$ pc, and $\alpha = 1.4$ at $r < c$ and $= 2.0$ at $r > c$ (G03).

The cloud used in this experiment is spherical with a radius of 15 pc, a mass of $4.3 \times 10^4\, M_\odot$, and a temperature[1] of 10 K. It is seeded with supersonic turbulent velocities and marginally self-bound. A total of 2 155 660 particles were employed, thus the particle mass is 0.02 $M_\odot$. To simulate interstellar turbulence, the velocity field of the cloud was generated on a grid as a divergence-free Gaussian random field with an imposed power spectrum P(k), varying as k^{-4}. This yields a velocity dispersion $\sigma(l)$, varying as $l^{1/2}$, chosen to agree with the Larson scaling relations (Larson 1981). The velocities were then interpolated from the grid to the particles. Finally, the condition that the cloud be marginally self-bound gives a normalization for the global velocity dispersion of 3.8 km s^{-1}. The centre-of-mass of the cloud is initially at 25 pc from the SMBH. The orbit of the cloud was chosen so that the impact parameter with respect to the SMBH is 10^{-2} pc and the initial velocity is one tenth of the escape velocity from the SMBH at the initial distance (i.e. the orbit is bound and highly eccentric). As the tidal density at ~ 25 pc from the GC is higher than the average initial density of our cloud, our marginally bound cloud must have formed further out and then migrated closer to the GC. Various processes could have brought the cloud in such position. For example, the cloud might have achieved this orbit after a collision with another cloud. On the other hand, the existence of two giant molecular clouds, M$-0.02 - 0.07$ and M$-0.13 - 0.08$, at ~ 7 and ~ 13 pc, respectively, from the GC (Solomon et al. 1972; Okumura et al. 1991; Ho et al. 1991; Novak et al. 2000) shows that molecular clouds, probably unbound, exist at $\lesssim 20$ pc from the GC. The cloud is assumed to be isothermal. This assumption neglects the local variations of the effective equation of state, that might occur due to the fact that the balance between heating and cooling processes depends on local conditions (see Section 4). In this Letter we focus on this case, as we want to present, in a concise way, our basic idea, preliminary simulations and findings. In a forthcoming paper we will carry out a parametric study considering different initial positions and velocities, different masses and a varying internal structure of the cloud, as well as different equations of state.

SF in the cloud is allowed by means of sink particles, as in NCS07. We use an upgraded version of the parallel N-body/SPH code GASOLINE (Wadsley, Stadel & Quinn 2004) in which sink particles have been implemented according to criteria widely used in the literature (Bate, Bonnell & Price 1995). We adopt a sink accretion radius $r_{acc} = 5 \times 10^{-3}$ pc, similar to the softening length ($\epsilon = 5 \times 10^{-3}$ pc). We calculate a density threshold $\rho_{thr} = \Omega\, c_s/(2\,\pi\, G\, h\, Q) \simeq 10^6$ cm^{-3} (where Ω is the angular velocity, c_s the sound speed, G the gravitational constant, h the scaleheight of the disc and Q is the Toomre parameter), by imposing that $Q = 1$, according to Toomre's criterion for gravitational stability appropriate for rotating gaseous discs. Gas parcels that are unstable based on the Toomre criterion are always well resolved thanks to our mass resolution. [2] (Toomre 1964). Whenever a gas particle reaches this density threshold and its smoothing length is less than $0.5\, r_{acc}$ (so that at least ~ 50 particles are inside r_{acc} - for comparison in GASOLINE a single SPH kernel comprises 32 particles), it is considered a 'sink candidate'. If gas particles inside the accretion radius of the sink candidate satisfy Bate's criteria[3], then the candidate

[1] A temperature of 10-30 K is consistent with the one predicted for dense gas in regions of moderate star formation (Spaans & Silk 2000). Test simulations show that our results do not change significantly for isothermal clouds with temperature up to ~ 50 K.

[2] The exact value of the density threshold is not crucial for our findings since values of ρ_{thr} between 10^3 and 10^8 cm^{-3} give approximately the same results. This is due to the fact that, given the high densities reached in the disc around the SMBH, the density threshold is easily reached, whereas the other criteria are more difficult to satisfy.

[3] Bate's criteria for converting gas particles into sink particles require (see section 2.2.2 of Bate et al. 1995) i) that the thermal energy of particles inside r_{acc} is $E_{th} \leq 0.5\, E_g$, where E_g

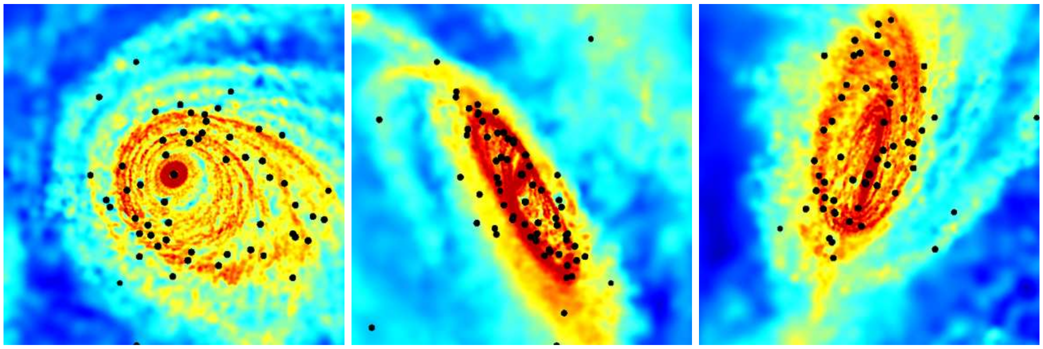

Figure 2. Density map of gas in the central disc, projected along the $x-$ (left-hand panel), $y-$ (central panel) and $z-$axis (right-hand panel) at $t = 4 \times 10^5$ yr. The frames measure 1 pc per edge. The density goes from 2.23×10^2 to $2.81 \times 10^4\ M_\odot$ pc^{-2} in logarithmic scale. The superimposed filled black circles are the sink particles. The sink particle at the centre of the frames is the SMBH.

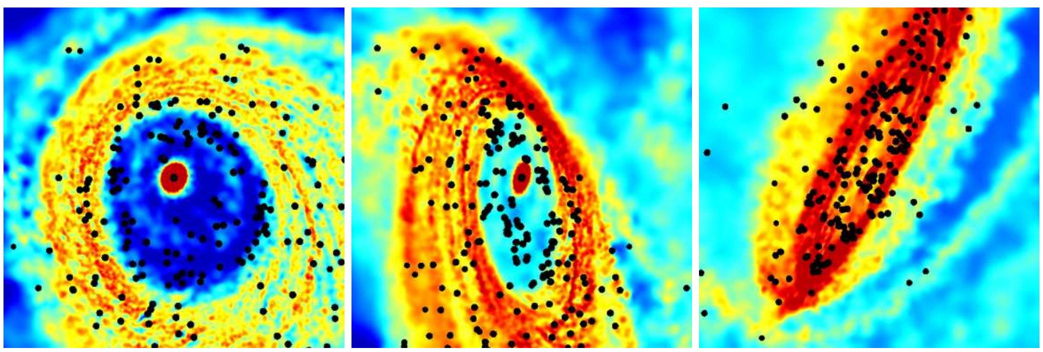

Figure 3. Density map of gas in the central disc, projected along the $x-$ (left-hand panel), $y-$ (central panel) and $z-$axis (right-hand panel) at $t = 5 \times 10^5$ yr. The frames measure 1 pc per edge. The density goes from 2.23×10^2 to $1.12 \times 10^4\ M_\odot$ pc^{-2} in logarithmic scale. The superimposed filled black circles are the sink particles. The sink particle at the centre of the frames is the SMBH.

becomes a sink particle. A similar procedure is followed to decide whether a particle which has already become a sink will accrete gas particles[4]. With this method we should be able to turn gas into stars according to the local properties of the cloud. This approach has many intrinsic limits (e.g. we do not follow the fragmentation of the cloud, but we replace this process with the formation of sink particles), but it is one of the best available approximations, up to date (see also NCS07). Furthermore, in the next section we will show that the results derived from the sink method are consistent with a different analysis based on Toomre's criteria for stability.

is the magnitude of the gravitational energy of the particles; ii) that $E_{th}/E_g + E_r/E_g \leq 1$, where E_r is the rotational energy of particles; iii) that the total energy of particles is negative.

[4] According to Bate's criteria (see section 2.2.1 of Bate et al. 1995) a gas particle within r_{acc} will be accreted by the sink particle if i) the gas particle is bound to the sink; ii) the specific angular momentum of the particle about the sink is less than required to form a circular orbit at r_{acc}; iii) the gas particle is more tightly bound to the considered sink particle than to other sink particles.

3 RESULTS

The cloud, orbiting around SgrA*, rapidly ($t \lesssim 10^5$ yr) stretches towards the SMBH and is partially disrupted. The branch of the cloud which points toward the SMBH begins to spiral in towards the GC (see Fig. 1). A dense, rotating gaseous disc forms at $t \sim 3 - 3.5 \times 10^5$ yr at the location of the in-spiraling branch. Its initial density is $\sim 1 - 5 \times 10^4$ cm^{-3} (assuming molecular weight $\mu = 2$), its outer radius is $r_{out} \sim 0.5$ pc and its initial mass is $\sim 330 - 1230\, M_\odot$. Such disc is not an homogeneous disc but is the assembly of many concentric annuli, which spiral around the SMBH, with slightly different inclination and thickness (lower panel of Fig. 1). The initial average thickness of the disc, defined as the ratio between the average scaleheight h and r_{out}, is ~ 0.1. Many spiral perturbations can be also seen in the disc at this stage.

At $t \sim 4 \times 10^5$ yr the disc has the average density of $\sim 2 \times 10^5$ cm^{-3}, but local densities of $\sim 10^{7-8}$ cm^{-3} are reached (see the density map of gas in Fig. 2). At this stage, the total mass of the gaseous disc is $\sim 2800 - 3100\, M_\odot$ and the parent cloud is still feeding it through a finger-like structure. The outer radius of the disc is still $r_{out} \sim 0.5$ pc and it does not change during the entire simulation. The disc appears distorted at the edges, where fresh gas is being fed by the parent cloud. Similarly, the orbits of gas particles

are quite eccentric on the periphery of the disc ($e \lesssim 0.5$) and almost circular at the centre ($e \lesssim 0.1$).

Stars begin to form inside the disc at $t \gtrsim 3.3 \times 10^5$ yr, i.e. immediately after the disc itself arises. Most of SF takes place between 3.5 and 5.0×10^5 yr. Between 3.3 and 4.0×10^5 yr 55 stars form in the disc. In the next 10^5 yr (i.e. between 4.0 and 5.0×10^5 yr) other 101 new stars form, and the total number of stars in the disc reaches 156. The total mass in stars at $t = 5.0 \times 10^5$ yr is $\sim 4900\,M_\odot$. Figs. 2 and 3 show the position of stars (black filled circles) superimposed to the density map of gas in the central disc, at $t = 4 \times 10^5$ yr and $t = 5 \times 10^5$ yr, respectively. As stars have formed inside the disc, the distribution of stars is also confined into a disc. The thickness of the stellar disc is $\sim 0.05 - 0.08$ and does not evolve significantly during the simulation. The outer radius of the stellar disc is $r_{out} \sim 0.5$ pc and does not change during the simulation. Stars which are corotating with the disc form only within ~ 0.5 pc, as the parent gaseous disc does not extend beyond ~ 0.5 pc. Only few stars have formed outside this radius (because the density rapidly drops below ρ_{thr}) and they are not corotating with the disc. This is in good agreement with the observations (G03; P06). Interestingly, the stellar disc has also an inner radius (r_{in}): no stars have formed inside $r_{in} \sim 0.06$ pc, as it can be seen from the left-hand panels of Figs. 2 and 3. This is in agreement with observations, which indicate that the stellar disc has a well-defined inner radius $r_{in} \sim 0.04$ pc. In the simulation, the existence of the inner radius is probably due to the fact that even the high central density of gas cannot counteract the Keplerian velocity at such small distances from the SMBH. In fact, Toomre's Q parameter, defined as $Q = \Omega\, c_s/(\pi\, G\, \Sigma)$ (where Σ is the local surface density, Toomre 1964), is $Q \gtrsim 5$ at radii $\lesssim 0.04$ pc. For such high values of Q, the growth of gravitational instabilities in the disc is unlikely. Thus, a very dense ($\sim 10^8$ cm^{-3}) gaseous disc, with a radius ~ 0.04 pc, survives around the SMBH during the entire simulation. On the other hand, although the softening length is ~ 10 times smaller than r_{in}, we cannot completely exclude that the existence of r_{in} is due to numerical effects. Higher resolution simulations are needed to address this issue. The comparison between Fig. 2 and Fig. 3 reveals another interesting feature: gas is being gradually depleted from the inner regions of the star forming disc. In fact, at $t = 5 \times 10^5$ yr (Fig. 3) the density of gas between ~ 0.05 and ~ 0.25 pc is much lower than at $t = 4 \times 10^5$ yr (Fig. 2). Correspondingly, the number of stars between ~ 0.05 and 0.25 pc in Fig. 3 is a factor of ~ 2 higher than in Fig. 2. Thus, gas is depleted from the inner parts of the disc, because it has been efficiently converted into stars. Second, the feeding from the parent cloud tends to decrease, and is not able to counter-balance gas consumption by SF.

After 5.0×10^5 yr, the SF rapidly declines. In fact, most of the densest gas within $r_{out} \sim 0.5$ pc has been converted into stars, and the remaining gas is not sufficiently dense to produce new stars. At $t = 6.0 \times 10^5$ yr the total stellar mass within the disc is $\sim 5850\,M_\odot$, and no significant changes have occurred either in the stellar distribution or in the mass function (MF) during the last 10^5 yr. At the end of the simulation ($t = 7.0 \times 10^5$ yr) the total stellar mass within the disc is still $\lesssim 6000\,M_\odot$, indicating that the SF process has almost stopped. This total mass is quite in agreement with the estimated value of $\sim 5000\,M_\odot$ and is well below

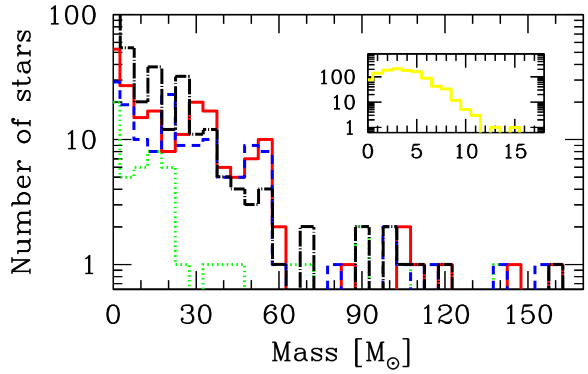

Figure 4. Stellar MF in the simulation. Dotted green line: $t = 4 \times 10^5$ yr; dashed blue line: $t = 5 \times 10^5$ yr; solid red line: $t = 6 \times 10^5$ yr. Dot-dashed black line: stellar MF in the simulation at $t = 6 \times 10^5$ yr when accounting for binary fraction. In the small insert: solid yellow line: MF in the isolated cloud ($t = 16$ Myr).

the upper limit of $\sim 1.5 \times 10^4\,M_\odot$ derived from observations of the discs around SgrA* (P06). As the parent gaseous disc was eccentric ($e \lesssim 0.5$) and was distorted in its outer parts, the stellar orbits have non-negligible eccentricities with a large spread ($0.1 \lesssim e \lesssim 0.7$) and different inclinations with respect to the disc plane (between ~ 0 and ~ 0.7 rad). This result is consistent with recent observations (P06; Cuadra, Armitage, Alexander 2008). At this stage, the entire parent cloud is stretched and very elongated toward SgrA*, its average density is ~ 55 cm^{-3} and its centre-of-mass is located at ~ 10 pc from the GC. These characteristics, and especially the elongation toward SgrA*, are quite similar to those of the molecular cloud M$-0.13 - 0.08$. The average accretion rate of the SMBH during the simulation is $\sim 5 \times 10^{-6} M_\odot$ yr^{-1}, below the gas capture rate inferred from X-ray observations ($10^{-5} M_\odot$ yr^{-1}; Baganoff et al. 2003) but a factor of 5 higher than the upper limit from polarization measurements (Marrone et al. 2006). However, this value must be considered a rough approximation, as we cannot describe the physics of the accretion around the SMBH.

Fig. 4 shows the stellar MF derived from our simulation at $t = 4$, 5 and 6×10^5 yr (dotted, dashed and solid line, respectively). After a fast initial evolution ($t < 5 \times 10^5$ yr), the MF does not change significantly between 5 and 6×10^5 yr. In the final MF most of stars have mass below $60\,M_\odot$. The number of OB and Wolf-Rayet stars detected in the GC up to date is ~ 73, and their inferred total mass is $\sim 3700 - 4300\,M_\odot$, assuming a mass range of $20 - 120\,M_\odot$ and an IMF $dN/dm \propto m^\Gamma$ with slope Γ between -1.35 and -0.85 (P06). In our simulation there are 90 stars in the same range of mass ($20 - 120\,M_\odot$), corresponding to a total mass of $\sim 3740\,M_\odot$. The agreement between data and simulation is quite good. A possible problem of the simulated IMF is the existence of a very high-mass tail. 13 stars in the simulations have mass higher than 60 $M_\odot$, and the most massive among them has $m = 202\,M_\odot$. The formation of excessively massive stars may be an intrinsic problem of the sink particle method. In fact, the use of sink particles does

not allow to resolve close binary systems (Klessen, Spaans & Jappsen 2007), but the fraction of binaries is known to be ~ 0.5, at least in the solar neighborhoods (Vanbeveren, De Loore & Van Rensbergen 1998). To account for this, we assume that half of the stars in the simulation are unresolved binaries, with equal mass components, and we Monte-Carlo sample the MF based on such assumption. The MF obtained with this procedure is shown by the dot-dashed black line in Fig. 4. In this case, the most massive star weighs $m = 161\,M_\odot$.

Nevertheless, the properties of the gaseous disc are consistent with the formation of massive stars. In order to show that, we have calculated the Toomre most unstable wavelength ($\lambda_{\rm mu} = 2\,\pi^2\,G\,\Sigma/\kappa^2$, where κ is the epicyclic frequency, Binney & Tremaine 1987), i.e. the wavelength at which instability first appears, when Q drops below unity in a differentially rotating disc. We find that, at $t = 3.9 \times 10^5$ Myr, $\lambda_{\rm mu}$ can be as large as $\sim 4.1 \times 10^{16}$ cm (at ~ 0.37 pc). The mass enclosed into a spherical volume of radius $\lambda_{\rm mu}$, $\sim 30\,M_\odot$, represents then the expected characteristic mass at which collapse takes place and nicely agrees with the typical stellar mass found in the simulations. For a further check, we also ran a simulation in which the cloud is isolated (i.e. SMBH and rigid potential are not present) and we derived the corresponding MF. In this case, SF starts much later ($t \sim 3$ Myr) and reaches a maximum at $t \sim 12$ Myr, approximately the dynamical time of the cloud. No stars with mass higher than $\sim 15\,M_\odot$ form in the isolated cloud (see insert in Fig. 4). Thus, we conclude that it is the dynamical interaction between the SMBH and the cloud, with the resulting formation of the disc, that triggers a top-heavy IMF.

4 CONCLUSIONS

We simulated the infall of a molecular cloud toward SgrA*. In the first $\sim 10^5$ yr the cloud is disrupted by the tidal forces of the SMBH and starts spiraling towards it. At $t \sim 3 \times 10^5$ yr a dense and small ($\lesssim 0.5$ pc) gaseous disc forms around the SMBH. Due to the high densities reached by the gas, stars begin to form in the disc. At $t \sim 5 - 6 \times 10^5$ yr most of gas has been depleted from the disc and converted into stars. The stars are distributed in a thin disc with $r_{in} \sim 0.06$ and $r_{out} \sim 0.5$ pc, similar to the one observed around SgrA* (G03; P06). The total stellar mass in the disc, $\sim 6000\,M_\odot$, is also in agreement with observations. We found that the MF of the simulated stellar disc is top-heavy. A simple estimate based on Toomre's most unstable wavelength predicts the formation of massive stars in the gaseous disc, in agreement with the results obtained from the sink particle method. Thus, our simulations suggest that the infall of a molecular cloud toward the GC is a viable scenario for the formation of the massive young stars around SgrA*. This is an important result, as the origin of the stellar disc around SgrA* was still a puzzle so far.

However, our method suffers from various limitations and assumptions. For example, the timescale of SF likely depends on the assumption of isothermal equation of state. We expect longer timescales for SF when, e.g., a polytropic equation of state with a variable adiabatic index γ is adopted, because the gas would become more pressurized against collapse. However, even a factor of ~ 5 longer timescale is in agreement with observations, which suggest that the formation of the stellar disc took < 2 Myr. Even the stellar MF might depend on the treatment of gas thermodynamics and on the recipe to initialize sink particles. In a forthcoming paper (Mapelli et al., in preparation) we will study the dependence of our results on the equation of state of the gas. Furthermore, only one stellar disc forms during this simulations, whereas observations suggest the existence of two different discs. It may be possible that two different clouds have produced two different discs with similar ages, or that the same inspiraling cloud has fed two discs at slightly different epochs. In conclusion, this paper represents the first attempt to understand the formation of massive stars around SgrA* by simulating directly the infall of a molecular cloud. The results are encouraging, but this scenario deserves further investigation with a more realistic model of the thermodynamics and SF in the interstellar cloud and in the disc.

ACKNOWLEDGMENTS

We thank B. Moore, E. D'Onghia, E. Ripamonti, S. Callegari and P. Englmaier for useful discussions. MM, TH and LM acknowledge support from the Swiss National Science Foundation.

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